Earthquake Investigation in the United States

SPECIAL PUBLICATION NO. 282

Revised (1962) Edition

U. S. DEPARTMENT OF COMMERCE

COAST AND GEODETIC SURVEY

WASHINGTON

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Luther H. Hodges, Secretary
COAST AND GEODETIC SURVEY
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INTRODUCTION

To the layman earthquakes are generally considered a very unusual type of natural phenomenon—an indication that something occasionally goes wrong deep down in the earth. To the seismologist who studies earthquakes from their scientific viewpoint they represent a process of nature as unceasing and routine as the winds that blow over the oceans. It is the purpose of this booklet to explain the more important facts of earthquake phenomena and to outline the part played by the Federal Government and various seismological organizations in dealing with the scientific and economic aspects of the earthquake problem. The booklet supersedes Serial No. 456 bearing the same title and published in revised form in 1929, 1952, 1953 and 1958.

SEISMOLOGICAL ORGANIZATIONS

The United States Coast and Geodetic Survey is authorized by law to make investigations in seismology, but other organizations in the United States are also engaged in such work. One of these is the Jesuit Seismological Association that coordinates the work of 23 affiliated seismological stations spread over most of the country. The California Institute of Technology operates 25 stations in southern California for the intensive study of earthquakes in that area, and the University of California operates a somewhat similar network of 21 stations in the northern California and western Nevada area. In addition more than a score of stations are operated independently by universities in connection with their geological and geophysical programs. One of the seismological functions of the Coast and Geodetic Survey is to serve as a clearing house for much of the statistical and other information collected by these various groups, to publish summaries of this information, and to fill in serious

voids in the instrumental program. In this collective effort to locate earthquakes accurately in the United States and elsewhere the Survey operates 14 stations of its own and actively cooperates in the maintenance of 14 others, mostly university stations. The United States Geological Survey operates seismograph stations on the Island of Hawaii to study local earthquakes due to volcanic activity.

It will subsequently be shown that, far from being exclusively of academic interest, the results obtained from this concerted effort are of practical use to many professional groups: to structural engineers and insurance actuaries who want to know exactly where, and to what degree, earthquake dangers exist; to structural engineers who want to know the magnitude and nature of the earthquake forces they must design structures to resist; to geologists who endeavor to associate seismic activity with the faults they map in the course of their field surveys; and to meteorologists who want to know just how the minute vibrations of the earth's surface that are unceasingly registered on seismographs are related to storms and other meteorological phenomena. In the academic field the study of seismic wave propagation has furnished the most authentic information yet obtainable on the physical nature of the earth's interior. The study of earthquake waves has also furnished the basic concepts used in locating oil-bearing structures by seismic exploration methods.

The program of the Coast and Geodetic Survey is a representative amount of the seismological work done in this country and includes projects of a highly specialized nature. Besides operating seismological stations to locate earthquakes it collects statistical information on all types of earthquake phenomena including damage, prepares earthquake catalogs and epicenter maps, and conducts various types of investigations directed toward a better understanding of earthquake phenomena.

One of the most important phases of the Survey's seismological program is the investigation of destructive earthquake motion, a program that is of basic importance to the engineer who must design structures to successfully resist earthquake forces. The 700 persons killed in the great Cali-

fornia earthquake of 1906 and the billion dollar (present-day value) property loss caused from the fires that followed will always stand as a warning to those who feel that the earthquake menace can be ignored. Years of study have shown that the problem of the design engineer is technically difficult because earthquake forces are vibrational or dynamic in character and cannot be treated the same as static, or steady, forces. Much has been accomplished, however, and the Survey has played an important role in this accomplishment through furnishing authentic information on destructive ground and building motions.

While the work of other seismological groups is devoted in part to the study of regional seismicity, the scope of their programs is extremely broad and includes such projects as world seismicity investigations, study of continental and oceanic structure by seismic exploration methods, the relation between microseisms and hurricanes, and scores of other projects many of which are closely related to other fields of science.

An interesting phase of seismological research is its international aspect. The fact that a strong earthquake in any country is registered on seismographs all over the world has resulted in a world-wide exchange of data and cooperative effort that is matched in few other fields. This international effort has resulted in a great accumulation of technical data that has not only made possible an authentic history of world earthquakes over the past 60 years but exhaustive analyses of the data have given the scientific world the most accurate picture it has of the physical structure of the interior earth.

WORLD EARTHQUAKES

It is estimated that more than a million earthquakes occur throughout the world annually. They range from minor temblors that are barely perceptible locally to catastrophic shocks. Fortunately most earthquakes originate beneath the sea where they cause little concern except when seismic sea waves are generated. Such waves occasionally cause damage and loss of life near the earthquake origins and also thousands of miles away. Approximately 700 of the million annual shocks may be classed as strong, capable of caus-

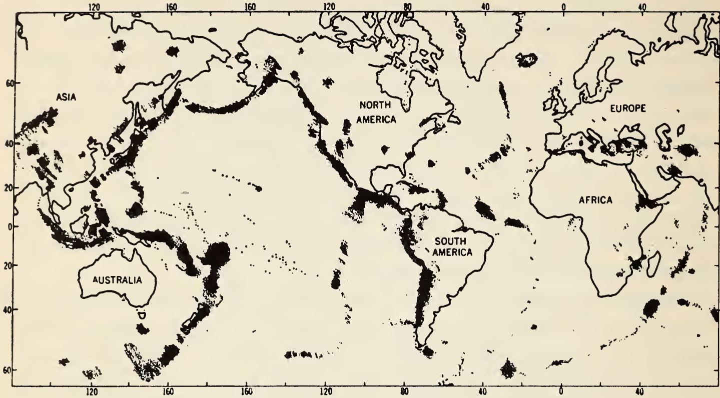

Figure 1.—*Earthquake belts of the world.*

ing considerable damage in the areas where they occur. The Coast and Geodetic Survey with the cooperation of many foreign and domestic agencies, locates most of these within a few hours or days. The annual epicenter maps that pinpoint these locations are illuminating exhibits that show where most earthquakes occur. One is struck not only by the existence of certain well-defined seismic belts stretching over large areas of the world, but also by the persistence with which the over-all pattern is repeated year after year.

The rim of the Pacific Ocean outlines the world's greatest seismic belt. This belt includes the Pacific coast and western mountain region of the United States and a large part of Alaska. A second major belt branches off to the west, extending across the southern portion of Eurasia, through the Mediterranean area, to the Atlantic Ocean. There are also many minor belts such as that looping eastward from the Pacific through Mexico, the West Indies (including the Windward Islands), and those countries bordering the southern shores of the Caribbean Sea. Earthquakes in all of these belts are taken for granted but great earthquakes also occasionally occur outside these zones. In this country southeastern Missouri and Charleston, S. C., are examples of such

areas, but in such cases many years usually elapse between destructive shocks. This brief outline shows that not only are the great cities of our Pacific coast vulnerable to destructive earthquakes, but the menace also exists in latent form in many areas ordinarily thought to be immune.

EARTHQUAKES IN THE UNITED STATES

The earthquake history of the United States is outlined in Coast and Geodetic Survey Serial Publication 41–1, *Earthquake History of the United States*, Parts I and II. Part I covers continental United States (exclusive of California and western Nevada) and Alaska; part II covers the stronger earthquakes of California and western Nevada. Both volumes are available for purchase from the Superintendent of Documents, Government Printing Office, Washington 25, D. C., at 60 cents and 40 cents, respectively. Information on recent earthquakes will be found in the annual issues of the *United States Earthquakes* series also published by the Coast and Geodetic Survey. The following is a résumé of the earthquake history of the United States based on information appearing in these publications.

Eastern Region

The earliest recorded earthquake of destructive intensity felt in the United States occurred in the valley of the St. Lawrence River in 1663, centering apparently between the present sites of Montreal and Quebec. Great landslides kept the river muddy for a month.

A less severe earthquake occurring in the same general region in 1870 was felt as far south as Virginia, but damage in the epicentral area was comparatively light. Another shock centering 300 miles west of this area, near Tamiskaming, Canada, shook most of the northeastern part of the United States on November 1, 1935. On September 5, 1944, a shock centering close to Massena, N. Y., and Cornwall, Canada, caused $2 million damage in these towns.

Various parts of New England have experienced moderate to severe earthquakes, some of sufficient intensity to damage houses, especially chimneys. The most severe was that of

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November 18, 1775, centering probably near Cambridge, Mass. Many chimneys were thrown down or twisted and roofs were wrecked by the fall of chimneys. In 1791 there were strong shocks near East Haddam, Conn., and for years the area was noted for subterranean noises of seismic origin. On November 18, 1939, all of New England was shaken by a strong submarine earthquake off the Grand Banks. A coastal area extending from Richmond, Va., to Portland, Maine, and inland as far as northwestern Pennsylvania, was shaken on August 10, 1884, by an earthquake that apparently originated near the edge of the continental shelf off the mouth of the Hudson River. On Long Island, walls and plaster were cracked at many places. The lake region of northeastern New York has experienced several shocks strong enough to damage chimneys. On August 12, 1929, Attica, in the western part of the State, experienced a shock that knocked down 250 chimneys.

In New Jersey, Pennsylvania, and the States to the south, occasional strong but nondestructive shocks are believed to be the result of the settling of the coastal plain sediments on the underlying basement rock that structurally represents the base of the Appalachian Mountain range. One of the strongest of this type occurred in Giles County, Va., in 1897, where old brick houses and chimneys were cracked. It was felt as far as Indiana and Georgia.

The greatest shock in the east was the Charleston, S. C., earthquake of August 31, 1886. It was felt in Chicago and Boston, and in contrast to most other shocks in this general area, was apparently of tectonic origin. In Charleston 60 persons were killed and many buildings were ruined or severely damaged. In the surrounding country bridges were wrecked, railroad tracks were twisted, and sand and water were ejected from numerous craterlets.

Mississippi Valley Region

Although this region is not considered seismic in the popular mind, in 1811 it was the scene of the greatest earthquake this country ever experienced—an earthquake rated as one of the great earthquakes of known history. It centered near New Madrid in southeastern Missouri and was felt over

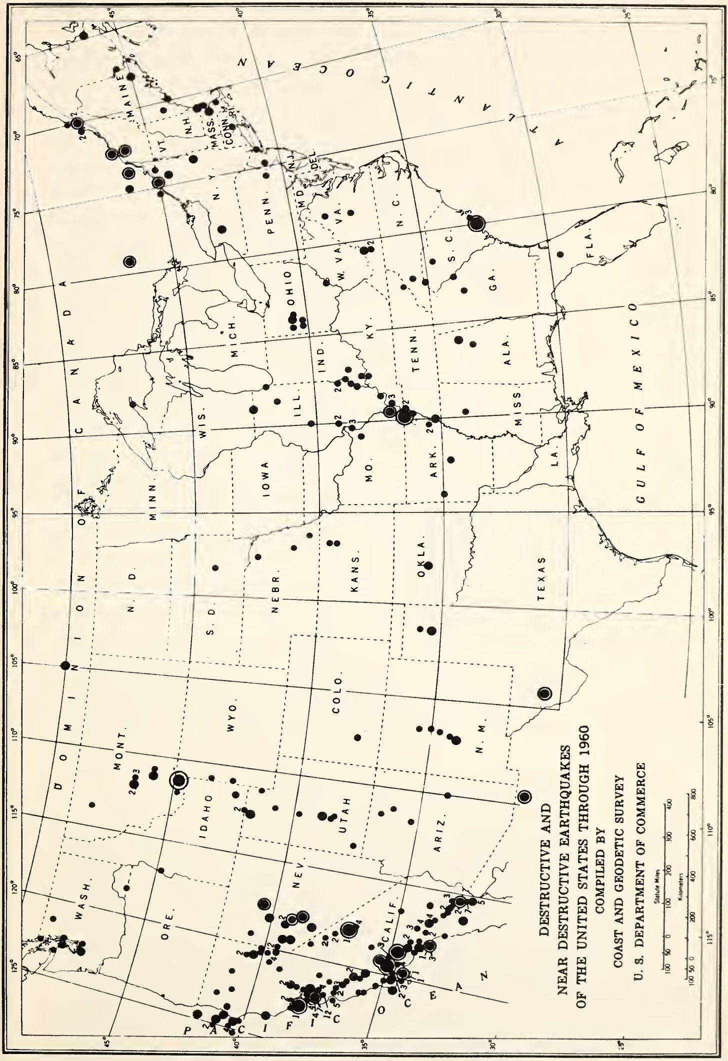

FIGURE 2.—*Coast and Geodetic Survey Epicenter Map of the United States.*

two-thirds of the United States. With this area of the country now so thickly settled, one can only conjecture what might happen if a disturbance similar to that of 1811 were repeated. Evidence exists that there was a similar earthquake in the same region about 100 years prior to the 1811 shock. A lasting result of the 1811 disturbance was the lowering of a large part of the countryside in southeastern Missouri and northeastern Arkansas now known as the "sunken country." In time of flood the sunken country, with its many lakes and bayous has served as a temporary reservoir for the flood waters of the Mississippi River, but in recent years levees have been built and the land cultivated, other measures having been taken to solve the flood problem.

Severe shocks were reported from the general area in 1843 and 1895 but hardly a year has passed without some disturbances being reported. The 1843 shock was felt strongly in St. Louis, Mo.; Frankfort, Ky.; Cincinnati, Ohio; and Nashville, Tenn. In 1895 a lake was formed over 4 acres of ground that sank near Charleston, Mo. Many chimneys were demolished. Near Bertrand sand was ejected from the ground and the water table was apparently raised. The shock was felt in 23 States.

Southwestern Indiana is a center of moderate activity. The central portion of western Ohio has experienced five strong shocks since 1875, most of which cracked some walls and toppled a small number of chimneys. Other centers of moderate activity are found scattered through Illinois and generally west of the Missouri River in eastern Nebraska and Kansas.

Western Mountain Region

Excluding Nevada from the picture, the principal seismic zone in this area extends in a broad band from Helena, Mont., southward to northern Arizona. Two destructive earthquakes centered close to Helena in 1935. In 1925 violent shocks in the region of Manhattan and Three Forks, Mont., cracked many buildings, toppled chimneys, and caused landslides that blocked the main line of the C. M. and St. P. Railroad for many days. In 1959, an eight-state area and British Columbia felt the Hebgen Lake, Mont., earthquakes in which

28 people were engulfed by the great Madison Canyon slide. Surface damage extended 50 miles westward from Yellowstone National Park; and the estimated timber and road damage exceeded $11 million. In 1934 a strong shock centering near Kosmos, Utah, caused many craterlets to form, cracked walls and chimneys locally, and caused some plaster to fall in Salt Lake City. At Elsinore, 150 miles south of Salt Lake City, a series of strong shocks in 1921 damaged half the buildings, knocked down many chimneys, and wrecked a school building. In New Mexico a long series of disturbances near Socorro reached a climax in 1906 when a brief series of strong shocks cracked some adobe walls and toppled others.

The Panhandle area of Texas has experienced a number of widespread but nondestructive shocks. In 1931, in the Great Bend area southeast of El Paso, a violent shock centering near Valentine badly damaged buildings of all kinds, knocked down many chimneys, and was felt over the entire State. Large quantities of water were emitted from cracks and craters that formed in the ground. Across the border in the State of Sonora, Mex., an earthquake in 1887 destroyed the church at Bavispe and damaged many other buildings. Great numbers of cracks emitted sand and water, and millions of cubic feet of rock were thrown down the mountains.

Pacific Coast and Nevada

Two-thirds of the seismic activity of the country is centered in this area, most of it in the coast ranges of California. Some of the outstanding historic earthquakes include one in 1812 in the Santa Barbara-Ventura-northern Los Angeles County region; one in 1838 along the San Andreas Fault near San Francisco; another in 1857 in the northwest corner of Los Angeles County; one in 1872 in Owens Valley in the Sierras; and finally the earthquake of 1906 which resulted in the destruction of a large part of San Francisco by fire. Other great earthquakes in this area include 2 that originated along the Haywards Fault just east of the southern half of San Francisco Bay; 2 submarine shocks off the northern coast of California; 2 in Nevada; and 1 each in the Los Angeles area, in Owens Valley, in Lower California, and in Imperial Valley. These were not necessarily

the most notable earthquakes because most of them expended their violence either in isolated mountain and desert areas or on the ocean floor. It is a fact, now seldom realized, that when the 1838 earthquake struck the Bay area, San Francisco was little more than a scattering of huts and crude structures familiar only to the early pioneers.

The California earthquake of April 18, 1906, was the most notable of all earthquakes in this country. Seven hundred lives were lost, and San Francisco was practically razed by fires that followed close on the heels of the earthquake. The city burned unchecked for days due to the wrecking of the water supply system. The actual earthquake damage probably did not exceed $25 million (1906 dollar value), but the fire increased this perhaps twentyfold. This scene of disaster was duplicated on a smaller scale in many other California cities and towns. The 1906 earthquake was the result of a readjustment of basement rocks along the San Andreas Fault, a great rift that extends from Imperial Valley, just north of the Mexican border, northwestward through the coast ranges to Golden Gate. A short distance north of Golden Gate it passes out to sea through an elongated bay—Tomales Bay—that was apparently formed by repeated movements along the fault over a long period of years. The maximum horizontal slipping in 1906 was 21 feet. Vertical slipping was only a small fraction of this. Along the fault fences and roads were sheared and separated many feet by the irresistible force of the earth movement. Structures built on the fault were wrenched and ruined.

The following is a brief summary of other notable earthquakes in the California-Nevada area. In 1868 almost every building in Hayward was damaged by a slip along the Haywards Fault, the damage in San Francisco reaching $350,000 (present-day value approximately $1 million). In 1872, at Lone Pine in Owens Valley, all adobe houses were wrecked and 27 persons out of a population of 300 were killed. In 1892 practically all brick buildings in Vacaville were wrecked. In 1899 nearly all brick buildings in San Jacinto and Hemet were damaged, only 2 chimneys being left intact in Hemet. Six persons were killed. The same towns experienced another shock in 1918 that wrecked all poorly constructed

buildings in the business areas causing more than $200,000 damage. In 1920 Inglewood experienced a highly localized disturbance in which many buildings were wrecked and few escaped damage. In 1925, Santa Barbara suffered several million dollars damage, few buildings on the main street—State Street—escaping damage. This disturbance which killed 13 persons was caused by a fault slip in the mountain ranges just north of the city.

In 1933, on March 10, 120 persons were killed and $41 million damage was caused by an earthquake that struck close to Long Beach. This was not potentially a great earthquake but the zone of greatest energy release seems to have been only a few miles away—in or near the Signal Hill area. On May 18, 1940, an earthquake slightly greater than Long Beach centering near Imperial in Imperial Valley caused $6 million damage and killed several people. It was featured by a horizontal fault movement of 15 feet. On June 30, 1941, another shock near Santa Barbara resulted in $100,000 damage and on November 14 of the same year the Torrance-Gardena area of Los Angeles county suffered $1 million damage. In 1949 a minor disturbance centering on Terminal Island in San Pedro Bay sheared 200 oil wells near the 1,700-foot level causing more than $9 million damage. In 1951, 1955 and 1961, earthquakes barely perceptible at the surface caused additional subsurface damage ($3, 3, and 4.5 million respectively) to oil wells on Terminal Island and adjacent mainland. On July 21, 1952, the strongest earthquake to hit California since 1906 shook the area south of Bakersfield. The main shock and the series of strong aftershocks that followed killed 14 people and caused an estimated $60 million damage to buildings, railroads, and crops. It was caused by a slip along the White Wolf Fault, one of the more obscure faults that parallels the Garlock Fault about 20 miles northwest of the latter. The hardest hit towns were Arvin and Tehachapi although more damage occurred in Bakersfield because of its greater size. Bakersfield was badly shaken not only by the main shock but also by a strong aftershock that centered very close to the city on August 22. On December 21, 1954, Eureka and Arcata were violently shaken and nearly every building suffered

structural damage. The reported damage was $2 million in Eureka and in Arcata $100,000; one fatality in Eureka. On October 23, 1955, a strong shock between Concord and Walnut Creek caused the death of one person and $1 million property damage. The San Francisco Bay area earthquake on March 22, 1957, caused cracked highway pavements, landslides, broken windows, and cracked a reinforced concrete water reservoir. Over-all damage amounted to $1 million.

A swarm of earthquakes from July through December 1954 near Fallon, Nevada in the Stillwater and Clan Alpine mountains ranged in intensities from VII through X, and caused great surface ruptures, with damage to canals and drainage systems, irrigation structures, and paved highways. The area being sparsely settled experienced little property damage, mostly in Fallon. Of particular interest was the 5–15 feet of vertical movement in the Dixie Valley and east of Fairfield Peak 6–20 feet of vertical and 4–12 feet of horizontal movements.

The Puget Sound area has always been known to be moderately seismic with a record of a few hard jolts at long intervals, but a step-up in activity during the past 10 years was climaxed by the strongest shock of all on April 13, 1949. More than $25 million damage was caused in cities bordering the Sound and several persons were killed. A shock in 1946 caused about $250,000 damage in Seattle, and several others were only slightly less severe. An unusually strong and widely felt shock in 1936 centered in northeastern Oregon in an area that was not thickly populated.

The greater violence and damage associated with Pacific coast and Rocky Mountain earthquakes as compared with those in the east is generally attributed to their shallower foci. Most of the major rock fractures in California appear to be only 10 or 15 miles deep whereas in other areas this may be doubled or tripled, thereby causing less violent motion at the surface.

Alaska

Alaska is one of the important links in the great seismic belt that circumscribes the Pacific. In the Aleutians many submarine shocks occur in and near the deeps that parallel the islands on the south side. This belt moves inward on

the Alaskan Peninsula, widens out in the region of the Kenai Peninsula, and extends northward into central Alaska, the region of Fairbanks marking the northern terminus. The Anchorage area is frequently shaken by earthquakes that would cause severe damage in a more thickly populated region. Just east of this active area is a quiescent zone but as the Canadian border is approached another active zone begins. This extends from the region around the southern half of the border to the southern portion of southeastern Alaska and on into British Columbia. Most of the shocks center inland.

In 1899 the Yakutat Bay area near the southern tip of the Canadian boundary experienced one of the notable earthquakes of the last century. The shore was raised over a considerable length, and at one point there was a vertical fault slip of 49 feet—one of the greatest fault movements known. On July 9, 1958, a major shock, the strongest in southeastern Alaska since the Yakutat earthquake of 1899, was felt as far south as Seattle, Washington, and eastward to Whitehorse, Yukon Territory. Three persons were killed on Khantaak Island in Yakutat Bay, and a fishing boat with two persons was missing after being caught by a huge wave in Lituya Bay. The wave in Lituya Bay was reported to have reached a height of 1,800 feet, either by avalanche, wave action, or a combination of the two.

Hawaiian Islands

Seismic activity in the islands centers on the island of Hawaii which is the largest as well as the farthest east in the group. Hawaii is best known for the spectacular eruptions of Kilauea Volcano and the lava flows that frequently break from the slopes of 15,000-foot-high Mauna Loa. While there are an abundance of strong tremors directly associated with volcanic activity some of the heavier shocks that are felt at times over all the islands as far as Honolulu seem to be of tectonic origin. These epicenters trend generally in a northeast-southwest direction and may originate on shore or beneath the sea. An earthquake in 1868 was extremely violent and destructive, considering the sparsely settled nature

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of the island. Hilo on the northeast coast frequently suffers severe earthquake damage. Strong submarine shocks off the southwest coast occasionally cause considerable damage nearby while those to the north and east may be felt with nearly equal violence on several islands.

Puerto Rico and Panama Canal Zone

Puerto Rico is in the loop or belt of seismic activity that extends eastward through the West Indies from the Pacific. Many strong shocks in this area have their origins in ocean deeps. A violent shock in the deep off the northeastern coast of the Dominican Republic caused widespread destruction in that country on August 4, 1946, and was strongly felt all over Puerto Rico. Violent shocks have also originated near the islands just east of Puerto Rico. The most notable disturbance in recent years was that of October 11, 1918, originating in Mona Passage at the northwest corner of the island. The damage in Mayaguez and nearby towns was great. Of the earlier shocks, that of 1867 was the strongest. While some moderately strong shocks have originated on the island itself the greatest menace has been from those of submarine origin.

Strong earthquakes do not originate in the Canal Zone itself nor in the portions of Panama immediately adjacent to it, but these areas are occasionally shaken by earthquakes originating in western Panama or northwestern Colombia. The main seismic belt of the Pacific bypasses the Canal Zone to the southwest but submarine shocks from this area are sometimes felt strongly there.

SEISMIC SEA WAVES

Submarine earthquakes occasionally generate seismic sea waves that travel thousands of miles over the oceans and cause great damage to shore property when they either pile up and break, or simply flood shoreline areas. Many ships have been carried ashore by such waves and hundreds of lives have been lost particularly in South America and Japan. On April 1, 1946, sea waves generated by a submarine earth-

quake in the Aleutian Islands caused $25 million damage in the Hawaiian Islands. Hilo was hardest hit. A lighthouse high on a cliff a few miles from the epicenter off Unimak Island was washed away and its five occupants drowned. At sea, in deep water, destructive seismic sea waves are seldom detected by ships because the distances between crests may be of the order of 50 miles and the wave height probably only a few feet or yards. It took the seismic sea waves of 1946 about 5 hours to travel from the Aleutian Islands, where the earthquake originated, to the Hawaiian Islands.

On March 9, 1957 another major earthquake, magnitude 8–8½, in the Andreanof Islands, Aleutian Islands, generated disastrous sea waves that caused extensive damage, about $3 million, on Oahu and Kauai, T. H., and on Adak and other nearby islands. A 40-foot wave boomed into the area where the Scotch Cap Lighthouse was completely destroyed in 1946. Unusually large waves were reported by many of the islands of the Pacific, along the west coast of North and South America, and the Japanese Islands, but little or no damage occurred. The major tremor was accompanied by a swarm of more than 290 aftershocks with 14 having magnitudes above 6¾. The tsunami which originated off the coast of Chile on May 22, 1960, devastated the adjacent coastline, inflicting heavy loss of life and property damage. In Hawaii, 61 lives lost at Hilo and damage about $22 million, although 6 hours of advanced warning was given by the Coast and Geodetic Survey's Seismic Sea Wave Warning System; in Chile, earthquake and tsunami caused more than 2,000 deaths and damage of $550 million; in Japan, 138 dead or missing and about $50 million in damages; in the Philippine Islands, 32 dead and missing; and along the west coast of the United States about $500,000 property damage. Unusually large waves were also reported on other Pacific islands.

A seismic sea wave is due to a sudden rising or dropping of the ocean floor. In some areas like the northeastern coast of Japan, where destructive sea waves from nearby submarine shocks are frequent and destructive, the coastal populations race for the hills as soon as strong shocks are felt. This saves thousands of lives.

NATURE OF EARTHQUAKES AND SEISMIC WAVES

Locating Earthquakes From Instrumental Data

Strong earthquakes are usually due to the rupturing of great masses of rock many miles beneath the surface of the earth. This generally takes the form of slipping or sliding along a rupture plane, called a fault. The repeated occurrence of earthquakes along the same fault over a long period of years is not unusual. Judging from the ground displacements observed after great earthquakes these fault slips may be as much as 50 feet as previously mentioned in connection with the Yakutat Bay, Alaska, earthquake of 1899. In some seismic areas such as Japan, geodetic surveys often show that great blocks of rock, tens of miles in dimension, undergo tilting. The ultimate cause of this continual adjustment of crustal rock is thought to be due to a slow but relentless flowing or creeping of the underlying ultrabasic rock that has persisted through geological ages. These rocks behave as plastic material which, like a mass of paraffin, will change shape without fracture if the distorting forces are applied slowly and steadily enough, but will crack if they are applied too quickly. The cause of this rock flow is largely a matter of conjecture. It could be due to cooling of the earth, convection currents set up by radio activity in the deeper rocks, changing loads on the surface due to the transfer of material through erosion and deposition, or other causes.

The great majority of so-called shallow earthquakes originate at depths of 10 or 20 miles but some are deeper, extending to a maximum depth of 450 miles. Earthquakes due to volcanic activity may seem violent locally but they are never very deep or felt at great distances. Compared with tectonic earthquakes that are frequently registered on instruments all over the world, they are very superficial.

Earthquakes cannot be predicted with respect to time and place except in terms that have little or no meaning. When the history of any seismic area is studied the pattern of earthquake occurrence is found to be so complex and erratic that it is quite impossible to derive from the data a formula that could be used to predict future disturbances. The gravitational pull of the planets is not sufficient to cause earthquakes nor has it been demonstrated that such stresses

are sufficient to always serve as trigger forces in setting off earthquakes that are just about ready to occur. In some places large areas of terrain move slowly along with the creep or flow of the deep basement rock and when the pattern of this movement shows that some sections of the rock are "stuck" and obviously building up stresses that will eventually cause fracture, it is clear that the stage is set for an earthquake in that area. Such a condition exists along the San Andreas Fault in California where precise geodetic surveys have shown that since 1906 the terrain on one side of the fault has moved about 10 feet relative to the terrain on the other side. One must assume that sooner or later the stresses building up in between will again fracture the rocks along the fault; that the crustal rocks and overlying terrain will again slide along the fault or surface of fracture; and that in a matter of seconds a new state of stress equilibrium in the rock will be established. One might logically predict earthquakes in such areas but the time of occurrence will always be in doubt until the complete histories of a number of earthquake cycles are thoroughly known. In Japan some

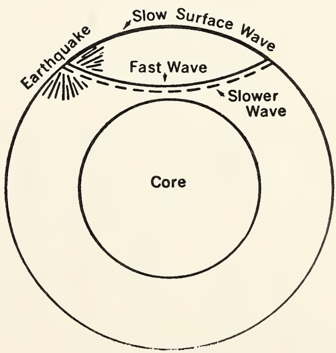

FIGURE 3.—*Paths of principal earthquake waves. Earthquake waves radiate in all directions through the earth's interior. The two curved lines show paths taken by those portions of the waves that travel between the earthquake and seismograph station. The surface waves travel only through the crust.*

successful predictions of strong shocks apparently have been made through the discovery that certain changes in terrain and certain earthquake sequences form a pattern that seems to repeat itself after each great shock in the area under study.

When great masses of rock are fractured, violent vibrations are radiated in all directions through the rock and overlying soil. It is the force of these vibrations that causes damage and frightens people in earthquake areas. On the lighter geological formations that overlay the ruptured basement rocks the force of the vibrations may be increased 5-, 10-, or 20-fold, increasing in severity with the lightness of the rock or soil and the height of the local water table. This accounts largely for the lack of uniformity in the damage experienced in a community shaken by an earthquake, but much, too, depends upon the sturdiness of individual buildings.

In a great earthquake these seismic vibrations or waves penetrate the entire structure of the earth and travel all over its surface. While great earthquakes are seldom felt farther than a thousand miles from their source, sensitive seismographs have registered these unfelt vibrations in all parts of the world for more than 50 years. Such seismic waves are extremely complex but a few basic facts will serve to explain how they are propagated through the earth and how the distance to an earthquake can be determined from a seismograph record.

Two types of waves travel at different speeds through the earth's interior and are known as interior waves. The faster one alternately compresses and dilates the rock as it travels forward; the slower one shakes the rock sidewise as it advances—like the vibration of a violin string. Seismological tables, based on many thousands of seismograph readings, show to the nearest second just how long it takes each of these wave groups to travel to points on the earth's surface at various great circle distances from an earthquake origin. The difference in the arrival times of two such wave groups at a seismograph station therefore corresponds to some particular epicentral distance that is shown in the seismological tables. These two waves are usually well defined on seismograph records and anyone who can recognize them can obtain the corresponding epicentral distance from the seismological

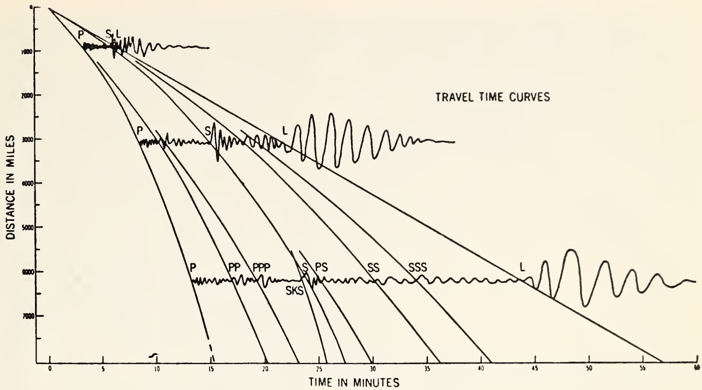

FIGURE 4.—*Travel-time curves with idealized seismograms superposed to show how time intervals between the principal waves listed in seismological tables correspond to the same time intervals on seismographic records. The time intervals always increase as the epicentral distances of the recording stations increase.*

tables. The largest waves recorded at distant stations, however, are usually waves that travel at nearly uniform speed through the surface rocks only and are known as surface waves. Until very recently epicenters were located on large terrestrial globes by swinging arcs around several observatory locations, using as radii the epicentral distances determined from the station records. Now they are being processed by modern electronic computer technics, thereby permitting the determination of many more earthquake locations in an equivalent amount of time.

From about 144,000 earthquake messages sent annually by telegraph, radio, and other means to the Coast and Geodetic Survey office in Washington, nearly 2,500 earthquakes are located within a matter of a few hours or days after their occurrence depending upon the violence of the shocks and the number of reports received. This represents only about 10 percent of the total number of earthquakes ultimately reported in this program. The press and the public thus

FIGURE 5.—*Geophysicists of the Coast and Geodetic Survey locating an earthquake on a 32-inch globe.*

obtain immediate and authentic information on all of the stronger shocks. Seismologists throughout the world use the information for various types of scientific research and to insure correct interpretations of current seismographic records.

Besides registering earthquake vibrations seismographs may also record ground vibrations from quarry blasts and other violent explosions. The distance at which such a disturbance may be recorded depends upon the strength of the blast, the distance to the recording station and the amplifying power of the seismograph. Although records of blasts and local earthquakes are frequently recorded on seismographs, the average type of instrument does not furnish a good record of the high frequency waves generated by them and interpretation is consequently difficult. The difficulty can be over-

come by choosing a seismograph of a type that will give satisfactory recordings of high frequency waves.

SEISMIC SEA WAVE WARNING SERVICE

One of the important services of the Coast and Geodetic Survey is the maintenance of a seismic sea wave warning program. The principal objective is to alert military installations on Pacific Islands and public officials in such areas as Hawaiian Islands and west coast of the United States whenever seismographic records reveal the occurrence of a submarine earthquake that might generate a destructive sea wave. Such a program would generally be impractical in areas near earthquake origins, but when 5 or 10 hours elapse between the time an earthquake occurs and the time sea waves might pile up on a distant shore there is time, by working fast, to locate the earthquake, establish the existence of a sea wave, and issue warnings to coastal populations that might be endangered.

In Hawaii, Alaska, Arizona and Guam, the Survey operates visible-recording seismographs that ring alarms whenever an unusually strong shock is being registered. Eleven other seismograph stations in various countries participate in this operation. Observers at 29 tide stations scattered over the Pacific immediately report unusual tidal disturbances to the monitoring station near Honolulu. A high-priority communications service is maintained between reporting agencies through the combined facilities of the Defense Communication Agency, Federal Aviation Agency, and the National Aeronautics and Space Council. With all of these groups functioning, the Survey's central station near Honolulu is enabled to locate a submarine shock and verify the existence of a seismic sea wave within 2 or 3 hours.

SEISMOGRAPHS

Seismographs are basically nothing more than carefully constructed pendulums that swing back and forth as the earth vibrates under them. Many seismograph pendulums take 10 or even 20 seconds to make a complete swing. The reason for this is that most waves from distant earthquakes have long periods and long wave lengths and it requires a

long-period pendulum to obtain a measurable difference between the moving pendulum and the moving ground. In nearby earthquakes, however, the ground vibrations are of short period and almost any kind of simple short-period pendulum would suffice. A long period is obtained by swinging the pendulum in a nearly horizontal plane about a nearly upright post, like a gate or door that is slightly tilted. It always takes a steady position in the direction in which the hinges are tilted. These are called "horizontal pendulums." It requires two such pendulums, and another that measures vertical motion, to obtain the complete motion of the ground at a seismograph station.

The second important requirement of a seismograph pendulum is that it must be damped to prevent it from swinging mostly in its own free period and obscuring other shorter and longer periods that are present in the ground motion. Some seismographs are damped with oil; that is, a vane or paddle fixed rigidly to the pendulum mass moves to and fro in a container full of oil whenever the pendulum is forced into vibration. If such a pendulum is pulled to one side one inch and then released, and if it overshoots its original position of rest by 0.1 inch, the damping ratio is said to be 10

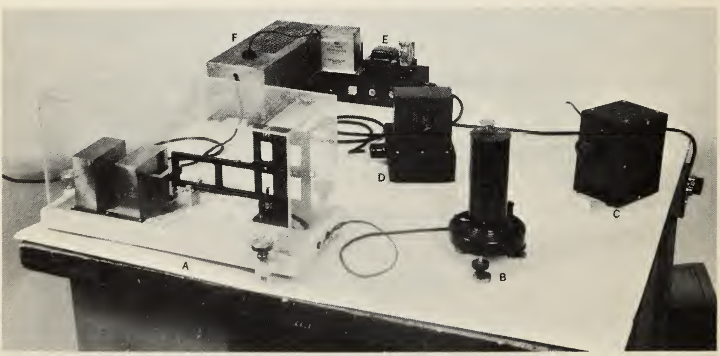

FIGURE 6.—*Modern seismometer with amplifying units. A—horizontal Sprengnether seismometer. B—galvanometer. C—light source. D—photoelectric cell and amplifier. E—power unit. F—voltage regulating transformer.*

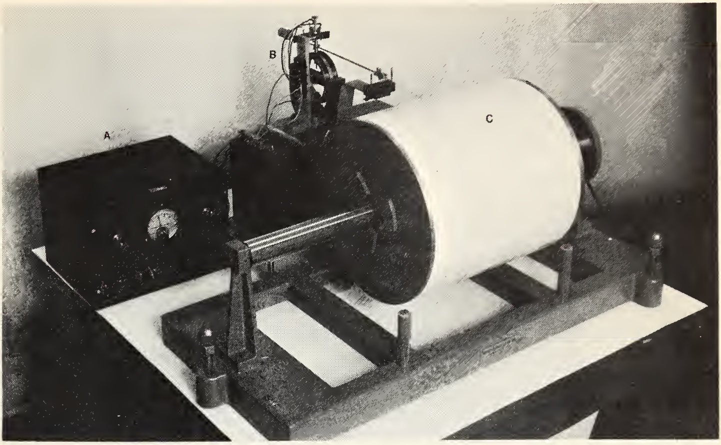

FIGURE 7.—*An assembly for visible-recording seismograph. Current is supplied from the seismometer assembly shown in figure 6 which is generally located in the basement of a building. A—control box. B—galvanometer and recording pen. C—revolving drum that registers all movements of the writing pen.*

to 1 which is about proper. Such a pendulum will give a good record of the ground motion. The great majority of modern seismographs, however, are not damped with oil but by a copper plate that passes closely between the poles of a powerful horseshoe magnet fixed to the instrument frame.

The third requirement of a seismograph pendulum is that its motion, relative to the ground, must usually be magnified many times by a mechanical lever system, by optical levers, or by electrical methods. Mechanical lever systems that magnify the pendulum motion from 10 to several hundred times are used on most older type seismographs. Such a lever in principle rotates horizontally on a pivoted vertical spindle set in jewel bearings that are fixed to the instrument frame. The short end is connected to the pendulum mass, while the long end that rotates through a much greater distance carries a delicately mounted steel pin or stylus that

scratches a fine line on a sheet of smoked paper that moves beneath it. In making records of this kind a strip of paper about a yard long and 6 inches wide is wound around a drum, then covered with a fine smoke film over a "sooty" flame and the drum set back on the seismograph recording mechanism. The drum usually turns through one revolution an hour and at the same time moves sidewise in a spiral so that 24 lines can be scratched on the paper without the lines overlapping. Whenever the pendulum is set into vibration by an earthquake a wavy line is scratched on the paper. This is the seismograph record and on it can be seen the principal seismic wave groups explained in the preceding section.

Greater magnification is obtained by dispensing with cumbersome mechanical levers and smoked paper and using beams of light that write fine lines on a sheet of photographic paper. This requires operating the seismographs in dark rooms that are characteristic of so many seismological stations. Such instruments are designed so that a mirror in the pendulum system rotates with the pendulum; consequently, when a fixed beam of light is reflected from the mirror onto the photographic recording paper it traces a wavy line during an earthquake just as in the case of the smoked paper recorder. Most seismographs using such systems magnify the pendulum motion one or two thousand times although special purpose instruments magnify as high as 25,000 times.

The greatest magnifications are ordinarily obtained with so-called electrical recording seismographs. In most of these a coil made of many turns of fine wire is fixed to the seismograph pendulum and forced by the earthquake motion to oscillate between the poles of powerful magnets fixed to the instrument frame. The current thus generated is sent through a sensitive galvanometer that makes a continuous record on photographic paper. With such instruments the ground motion can be magnified several hundred thousand times or more but this is greater than needed in most earthquake studies.

Seismographs made in this country to record destructive earthquake motions usually have very short-period pendulums, in fact, they are more like weighted springs. They

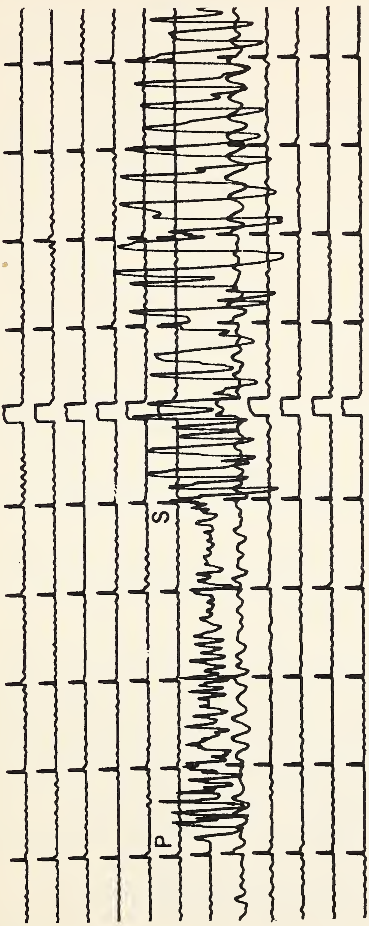

FIGURE 8.—*College, Alaska seismogram showing record of an earthquake on February 22, 1958, in the Andreanof Islands, Aleutian Islands. Time of origin 10h 50m 23s G.C.T. Epicenter 50½° N. Lat., 175° W. Long. Magnitude 6¾ according to Pasadena. Distance, 2,260 km.*

record the acceleration or force of the motion on photographic paper. Instead of operating continuously like regular seismographs they remain inoperative until a strong earthquake starts them. A starting pendulum closes an electrical circuit that causes the entire recording mechanism to operate for about 1.5 minutes. See figure 9.

Seismographs do not record the motion of the ground directly. The relationship between the actual ground movement and the movements shown on a seismograph record is very complex and will not be discussed here. It will suffice to say that when a seismograph is properly calibrated the seismologist knows just how much his instrument will magnify ground waves of all periods. This depends primarily on the pendulum period, the ground period, and a number of other factors, and explains why records of the same ground motion made with various type instruments can look so utterly different. Most important to the seismograph station director is the matter of keeping his time controls accurate to the nearest second. Earthquake waves pass the station at speeds as high as 5, 10, and 15 miles per second so that if he wants to determine earthquake distances from the arrival times of various wave groups he must be diligent with regard to time accuracy.

In the United States about 140 seismograph stations are in continuous operation. Throughout the world there are approximately 600 stations.

DESCRIPTIVE REPORTS ON EARTHQUAKES

One of the important functions of the Coast and Geodetic Survey is to collect descriptive information on earthquakes. This is done mostly from the San Francisco office of the Survey because most earthquakes occur in the Pacific coast and western mountain regions. The information is obtained from thousands of cooperators who keep earthquake questionnaire cards on hand, from postmasters and others in shaken areas who are canvassed immediately after an earthquake, and from field surveys made by seismologists who hurry to the scenes of destructive earthquakes immediately after they occur. This information is valuable not only for statistical purposes but it furnishes important data on the

earthquake intensity distribution in a shaken area. This is a complex phenomenon that is just beginning to be understood. The violence of an earthquake at a given distance from the epicenter depends not only on the strength of the earthquake at the focus but, as previously stated, largely upon local geological factors.

In this country the Modified Mercalli Intensity Scale of 1931 is used to evaluate earthquake intensity. It separates the violence of earthquake motions into 12 different grades. Grade I is such a feeble vibration that persons observe it only under very favorable circumstances such as lying quietly in bed with no distracting influences around. Grade VI represents earthquake motion that may cause superficial damage such as cracked windows, plaster, chimneys, etc. Grades XI and XII represent the most violent and destructive kinds of earthquake motions—vibrations that will flatten whole villages, destroy or damage most buildings in a large city, and cause disastrous mountain slides. Strong earthquakes frequently force water from the ground and flood local areas.

In recent years there has been much confusion in the press and in the public mind concerning the definitions of earthquake intensity and earthquake magnitude. Intensity is used to describe the severity or violence of an earthquake disturbance in any part of a shaken area and is based entirely on the earthquake effects reported on people and on inanimate objects, including damage. Magnitude, on the other hand, depends on the amount of energy released at the focus of an earthquake and is determined from the amplitudes of the ground vibrations registered at various seismological stations. Magnitudes are not reported in terms of energy but in terms of a mathematical function of the energy. The magnitude scale was developed about 25 years ago by seismologists of the Pasadena Seismological Laboratory of the California Institute of Technology.

ENGINEERING-SEISMOLOGY

The Survey's seismological program includes obtaining geophysical data needed by the structural engineer in designing safe structures in earthquake areas. The compila-

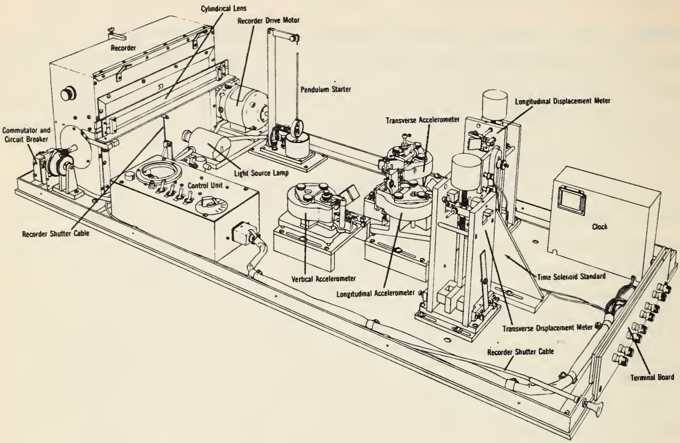

FIGURE 9.—*Coast and Geodetic Survey type accelerograph.*

tion of descriptive information and statistics on damage as just described is essentially a part of this program but the nucleus of it is a network of special seismograph stations operating on the Pacific coast, at various points in the western mountain region, and at a few places in Central and South America. The accelerograph used to obtain records of destructive earthquake motions at these stations was briefly described in the section on Seismographs. Seventy-seven such instruments now stand ready to record any strong or destructive earthquake motion in the areas named.

An accelerograph record shows the high frequency tremors of an earthquake best. They are the waves that have the highest acceleration, that are most often felt, and that do the most damage. In terms of actual ground motion (displacement) they are the waves of smallest amplitude. All of the longer period waves have much larger amplitudes. In order to obtain a complete picture of the motion the acceleration curve is put through a mathematical process called integration which produces another curve that shows the velocity of the ground vibration at any instant (not the speed of the wave through the ground). When this new curve is integrated the result shows the true movement of the ground in

inches. On this so-called displacement curve the high frequency waves are so small they are sometimes difficult to see, but the long-period waves are very clearly defined. Through this analytical process all of the periods and amplitudes involved in a complex earthquake motion can be determined and studied in detail.

Only recently has it been possible to associate the periods and amplitudes of destructive earthquake motions with the various grades of earthquake intensity according to the Modified Mercalli Intensity Scale of 1931. This has important significance in scientific and engineering investigations.

One of the engineers' difficult problems is to predict the motion, and consequently the stresses, in a building when it is subjected to a known earthquake motion. One approach is to assume that a building will respond to earthquake motions in "somewhat" the same way as a simple pendulum or vibrator that has the same vibration period as the building under study. Experience has shown, however, that it is a difficult problem to compute the response of even a simple vibrator to a complex earthquake motion unless costly computing machines are used. An interesting and simple device used for this purpose is the torsion-pendulum analyser. It has been found that when the torsion head of a simple torsion pendulum is turned through (positive and negative) angles that are proportional to the changing values of the linear ground acceleration (as registered on accelerographs) the mass of the torsion pendulum will turn through angles that are proportional to the linear displacements of the vibrator under study. In practice the entire torsion pendulum operation is slowed down one or two hundred times so that the effect of the earthquake motion on the vibrator is reproduced in slow motion.

Since it is clear that the natural periods of buildings and other structures play an important part in determining probable earthquake stresses it is necessary to measure the natural periods of many structures. To obtain this information the Coast and Geodetic Survey has made vibration measurements on more than 700 buildings and other structures in the Pacific coast and western mountain regions. After enough earthquakes have occurred it will be possible

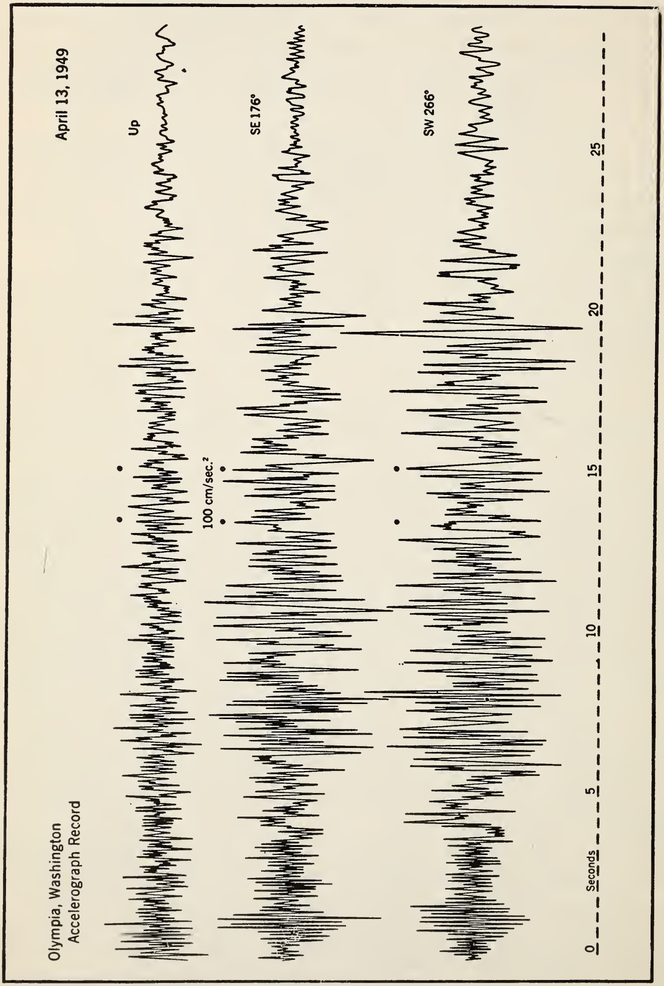

FIGURE 10.—*Olympia accelerogram of Puget Sound, Wash., earthquake of April 13, 1949.*

to tell how building damage may be related to the period of a building and to use this information in designing new buildings. Since buildings are always in a state of vibration, mostly from wind, their periods can be measured by setting up portable seismographs on the top floors.

A study of building damage reveals certain factual information that should be of interest to everyone concerned with the earthquake menace. To mitigate damage and possibly prevent injury and loss of life the following factors must be considered. First is the geological character of the ground itself. Soft ground, and especially fill, is definitely susceptible to greater intensity of motion than rock outcrops in the same area. Obviously special caution must be exercised in building structures on soft ground. More dangerous than this, however, is to build a structure partly on rock or hard ground and partly on soft ground, for then the differential motion between the two types of ground during an earthquake could wrench and damage a structure as much as if it were built on an active fault.

A great percentage of earthquake damage is undoubtedly caused by poor materials, especially mortar and plaster, that fail to hold up under earthquake forces. In many earthquakes old school buildings have furnished about the worst examples of poor construction materials. Equally bad is failure in many cases to tie the walls of brick structures to the interior framework, a step that frequently results in the collapse of entire walls while the rest of the building remains virtually intact. This holds true also for cornices, parapet walls, and other parts of a building. Frame houses should be tied well to their foundations or they may slide off.

The geometric pattern of a building is also important. Simple structures of rectangular cross section that sway as a unit without interference from other structures hold up best. When a building consists of two or more distinct parts that are not likely to vibrate in unison under seismic forces, the two parts tend to "hammer" each other, thus causing excessive damage or even collapse. In 1946 during one of the great earthquakes of the century off the coast of the Dominican Republic, a priest on the island actually observed

the battering action of the steeple on the auditorium section of his church and the eventual collapse of both.

These are simple but basic rules about building in earthquake areas that can be verified after almost any destructive shock. The truth is that after the strongest earthquakes experienced in this country one could find hundreds of buildings showing little or no damage mainly because they were well-designed and well-constructed in the first place.

WHAT TO DO WHEN AN EARTHQUAKE STRIKES

A very practical question about earthquakes is, "What should one do in an earthquake to escape injury?" First, remember that during an earthquake there is probably less chance of being injured than when taking a week-end automobile trip. Just about 1,400 persons have been killed in the United States by earthquakes and resulting tsunamis since the country was settled and 700 of these were lost in the California earthquake of 1906. Presumably very few of these were killed by the actual collapse of the structures they were in as pictures taken immediately after that shock show practically all buildings still standing, although damage was widespread. Most people were killed by rushing out-of-doors just as cornices, bricks, and other parts of buildings were crashing to the sidewalks and streets. Others remaining inside were injured or killed by falling chunks of plaster. The lesson to be learned is to get as quickly as possible under doorways, arches, tables, desks, or anything that will be a protection from a falling ceiling; but above all, do not rush into the street, at least without first taking a quick glance overhead. If you are on a sidewalk get off it as quickly as possible, either into an open doorway or the middle of the street if it is a wide one.

In many tropical countries the earthquake menace is made more serious by the widespread use of a weak lime mortar in building construction. Residents should reduce the hazard by observing building code provisions that have proved efficacious in other seismic areas. Tall, poorly braced frame structures with stone and lime mortar panels and walls are a particular menace especially when built on water-soaked

alluvial formations such as are so often found at the heads of bays and inlets.

Officials in seismic areas bordering on the open ocean should also be aware of the possible danger from destructive seismic sea waves that may sweep over low-lying coastal areas following a strong submarine shock. In most cases such waves are preceded by a clearly visible withdrawal of the water for a period of perhaps 5 or 10 minutes. This should be taken as a warning to shore residents to rush to high ground, for the returning water is bound to flood the low lands.

The most disconcerting feature of a destructive earthquake is not necessarily the temporary panic and destruction that follows the principal shock but the repeated occurrence of aftershocks that fills the populace with a hopeless sense of insecurity. The victims should first realize that such aftershocks follow all major earthquakes and may in some cases continue for months, but with decreasing frequency and violence. Some of them will be quite sharp but it is very seldom that one ever reaches the intensity of the main shock. Aftershocks generally center at various points in the epicentral area sometimes 15 miles or more from the source of the main shock. No seriously damaged building or home, however, should be reoccupied without the approval of local authorities. A building damaged by the main shock is made weaker by each aftershock. It is a false philosophy that argues that a damaged building will withstand strong aftershocks just because it withstood the main shock. Experience shows otherwise.

MICROSEISMS

The land surfaces of the world are no more in a state of absolute quiet than its water surfaces. Minute waves called microseisms are continuously moving through the rocks over the entire surface of the earth as can be seen by examining a sensitive seismograph record obtained in any part of the world. The most prominent and important waves have periods from about 4 to 7 seconds. In amplitude they range from approximately $1/25{,}000$ inch to $1/1000$ inch. There are others of much shorter period and smaller amplitude and of more localized character. These waves are all called microseisms.

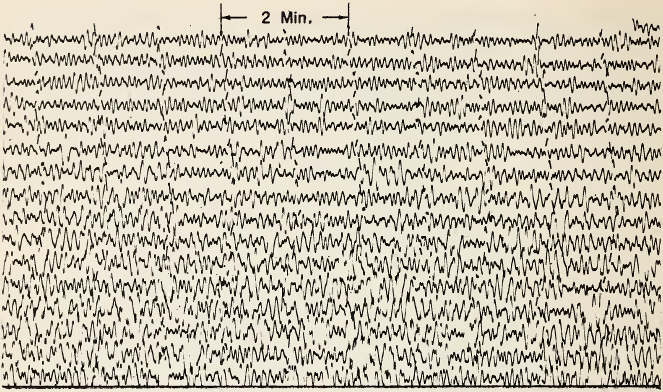

FIGURE 11.—*Seismogram showing microseismic storm of December 1 and 2, 1956 at Sitka, Alaska. Record was made on photographic recording seismograph. The increase in amplitude of wave motion was caused by a meteorological storm in the vicinity of southeast Alaska.*

Microseismic waves are of meteorological origin just the same as ocean waves; in fact ocean waves may play an important part in their generation. Regardless of the mechanism of their origin it is a fact that storms and low-pressure areas at sea are always accompanied by great increases in the amplitudes of microseismic waves recorded at seismographic stations in the surrounding coastal areas. In the West Indies microseisms have been recorded from hurricanes as far as 2,000 miles from the recording stations.

Cold-wave fronts and other forms of meteorological changes cause various unique types of microseismic disturbances that have been the subject of much interest and investigation among seismologists. The basic concepts that will satisfactorily explain the generation and propagation of microseismic waves are yet to be advanced.

Table 1.—***Active teleseismic stations of the United States and affiliated stations elsewhere***

COAST AND GEODETIC SURVEY AND COOPERATING STATIONS

Albuquerque, N. Mex	Coast and Geodetic Survey Seismological Laboratory.
Boulder City, Nev	Bureau of Reclamation.
Bozeman, Mont	Montana State College.
Butte, Mont	Montana School of Mines.
Byrd, Antarctica	Coast and Geodetic Survey Seismological Station.
Chicago, Ill	University of Chicago and U.S. Weather Bureau.
College, Alaska	Coast and Geodetic Survey Observatory.
do	Coast and Geodetic Survey Seismological Outpost Station.
Columbia S.C	University of South Carolina.
Eureka, Nev	Coast and Geodetic Survey Seismological Station.
Fayetteville, Ark.[1]	University of Arkansas.
Flaming Gorge, Utah	Bureau of Reclamation.
Glen Canyon, Ariz	Do.
Guam, Mariana Islands	Coast and Geodetic Survey Observatory.
Honolulu, Hawaii	Do.
Hungry Horse, Mont	Bureau of Reclamation.
Kipapa, Hawaii	Coast and Geodetic Survey Seismological Station.
Rapid City, S. Dak	South Dakota State School of Mines and Technology.
Salt Lake City, Utah	University of Utah.
San Juan, P.R	Coast and Geodetic Survey Observatory.
Sitka, Alaska	Do.
South Pole, Antarctica	Coast and Geodetic Survey Seismological Station.
Thule, Greenland	U.S. Army Ionosphere Station.
Tucson, Ariz	Coast and Geodetic Survey Observatory.
do	Coast and Geodetic Survey Telemeter Station.
Ukiah, Calif	Coast and Geodetic Survey Latitude Observtory.
Washington, D.C	Coast and Geodetic Survey Seismological Station.

See footnotes at end of table.

Table *1.—Active teleseismic stations of the United States and affiliated stations elsewhere*—Continued

JESUITS SEISMOLOGICAL ASSOCIATION STATIONS

Berlin, N.H	Weston Observatory.
Bloomington, Ind	Indiana University and Saint Louis University.
Buffalo, N.Y	Canisius College.
Cape Girardeau, Mo	Southeast Missouri State Teachers College and Saint Louis University.
Chicago, Ill	Loyola University.
Cincinnati, Ohio	Xavier University.
do	Outpost Station—Xavier University and Saint Louis University.
Cleveland, Ohio	John Carroll University.
Denver, Colo	Regis College.
Dubuque, Iowa	Loras College and Saint Louis University.
Florissant, Mo	Saint Louis University.
Little Rock, Ark	Saint John's Seminary and Saint Louis University.
Machias, Maine	Weston Observatory.
Manhattan, Kans	Kansas State University and Saint Louis University.
New York, N.Y	Fordham University.
Presque Isle, Maine	Weston Observatory.
Rollo, Mo	Missouri School of Mines and Metallurgy and Saint Louis University.
Saint Louis, Mo	Saint Louis University.
Spokane, Wash	Mount Saint Michaels College of Gonzaga University.
Spring Hill (Mobile Co.), Ala.	Spring Hill College.
Washington, D.C	Georgetown University.
Waterville, Maine	Weston Observatory.
Weston, Mass	Do.

PASADENA SEISMOLOGICAL LABORATORY STATIONS (CALIFORNIA INSTITUTE OF TECHNOLOGY) [3]

Permanent Stations in Continuous Operation

Barrett, Calif	Barrett Reservoir, City of San Diego.
China Lake, Calif	Naval Ordnance Test Station, Inyokern.
El Centro, Calif	Imperial Irrigation District.
Fort Tejon, Calif	Division of Beaches and Parks, State of California.

See footnotes at end of table.

Table 1.—*Active teleseismic stations of the United States and affiliated stations elsewhere*—Continued

PASADENA SEISMOLOGICAL LABORATORY STATIONS (CALIFORNIA INSTITUTE OF TECHNOLOGY)[3]—Continued

Permanent Stations in Continuous Operation—Continued

Goldstone, Calif	Jet Propulsion Laboratory. (Operating with provisional equipment pending permanent installation.)
Haiwee, Calif	Haiwee Reservoir, Bureau of Water Works and Supply, City of Los Angeles.
Hayfield, Calif	Metropolitan Water District, Los Angeles.
Isabella, Calif	U.S. Army Corps of Engineers, Sacramento.
King Ranch, Calif	E. R. King Ranch, McKittrick.
Mount Wilson, Calif	Mount Wilson Observatory.
Palomar, Calif	Palomar Observatory.
Palos Verdes, Calif	Palos Verdes Peninsula Unified School District.
Pasadena, Calif	Kresge and Donnelley Laboratories.
Riverside, Calif	City of Riverside.
Ruth, Nev	Kennecott Copper Corporation.
San Nicolas Island, Calif.	United States Navy.
Santa Barbara, Calif	Santa Barbara Museum of Natural History.
Tinemaha, Calif	Bureau of Water Works and Supply, City of Los Angeles.
Woody, Calif	Kern County Forestry and Fire Department.

Stations continuously operating on a temporary basis; subject to discontinuance or relocation

Alturas, Calif	U.S. Forest Service.
Albuquerque, N. Mex	Coast and Geodetic Survey; and Seismological Laboratory, Pasadena.
Jamestown, Calif	A. J. Industries, Los Angeles.
Klamath Falls, Oreg	Oregon Technical Institute.
Mineral, Calif	National Park Service, Lassen Volcanic National Park; and University of California.
Mount Shasta, Calif	Siskiyou Union High School.

See footnotes at end of table.

Table 1.—*Active teleseismic stations of the United States and affiliated stations elsewhere*—Continued

Stations continuously operating on a temporary basis; subject to discontinuance or relocation—Continued

UNIVERSITY OF CALIFORNIA STATIONS [3]

Arcata, Calif	Humboldt State College.
Berkeley (Haviland), Calif.	University of California.
Berkeley (Strawberry), Calif.	Do.
Calistoga, Calif	Do.
Concord, Calif	Diablo Valley College.
Ferndale, Calif	City of Ferndale.
Fresno, Calif	Fresno City College.
Llanada, Calif	University of California.
Manzanita Lake, Calif	Lassen Volcanic National Park.
Mineral, Calif	Do.
Mount Hamilton, Calif	Lick Observatory.
Palo Alto, Calif	Stanford University.
Paraiso, Calif	University of California.
Point Reyes, Calif	Do.
Priest, Calif	Do.
Reno, Nev	University of Nevada.
San Francisco, Calif	University of San Francisco.
Santa Cruz, Calif	University of California.
Shasta, Calif	Bureau of Reclamation.
Vineyard (Local), Calif	W. A. Taylor Winery.
Vineyard (Telemeter), Calif.	University of California.

INDEPENDENT STATIONS

Ann Arbor, Mich	University of Michigan.
Atlanta, Ga	Georgia Institute of Technology.
Baker, Oreg	Blue Mountains Observatory, Vela-Uniform Observatory; Technical Direction-AFTAC.
Balboa Heights, C.Z.[2]	The Panama Canal Company.
Bellingham, Wash	University of Washington.
Bermuda	Lamont Geological Observatory of Columbia University.
Blacksburg, Va	Virginia Polytechnic Institute.
Chapel Hill, N.C	University of North Carolina.
Corvallis, Oreg	Oregon State University.

See footnotes at end of table.

Table 1.—***Active teleseismic stations of the United States and affiliated stations elsewhere***—Continued

Stations continuously operating on a temporary basis; subject to discontinuance or relocation—Continued

INDEPENDENT STATIONS—continued

Dallas, Tex	Southern Methodist University.
Dugway, Utah	University of Utah.
Fort Sill, Okla	Wichita Mountains Observatory, Vela-Uniform Observatory; Technical Direction-AFTAC.
Golden, Colo	Colorado School of Mines.
Hawaiian Volcano Observatory.	U.S. Geological Survey.
Houston, Tex	The Rice Institute.
Laramie, Wyo	University of Wyoming.
Lawrence, Kans	University of Kansas.
Longmire, Wash	University of Washington.
Lubbock, Tex	Texas Technological College.
Madison, Wis	University of Wisconsin.
McMinnville, Tenn	Cumberland Plateau Observatory, Vela-Uniform Observatory; Technical Direction-AFTAC.
Minneapolis, Minn	University of Minnesota.
Morgantown, W.Va	West Virginia University.
New York, N.Y	City College of New York.
Ogdensburg, N.J	Lamont Geological Observatory of Columbia University.
Palisades, N.Y	Do.
Payson, Ariz	Tonto Forest Observatory, Vela-Uniform Observatory; Technical Direction-AFTAC.
Philadelphia, Pa.[2]	The Franklin Institute.
Pittsburgh, Pa	University of Pittsburgh.
Price, Utah	Carbon College of the University of Utah.
San Diego, Calif	Private Station. Fred Robinson.
Seattle, Wash	University of Washington.
State College, Pa	Pennsylvania State College.
Terre Haute, Ind	Private Station. Gerald Shea.
Vernal, Utah	Uintah Basin Observatory, Vela-Uniform Observatory; Technical Direction-AFTAC.
Waynesburg, Pa	Waynesburg College.

[1] Publishes own station bulletin.
[2] Results published by the Coast and Geoditic Survey.
[3] Correspondence with reference to the Pasadena and Berkeley network of Stations should be addressed to: Seismological Laboratory, 220 North San Rafael Ave., Pasadena; Seismographic Stations, University of California, Berkeley, Calif.

Table 2.—*Lives lost in major United States earthquakes*

Year	Place	Lives lost
1811	New Madrid, Mo	Several
1812	San Juan Capistrano, Calif	40
1868	Hayward, Calif	30
1872	Owens Valley, Calif	27
1886	Charleston, S.C	60
1899	San Jacinto, Calif	6
1906	San Francisco, Calif	700
1915	Imperial Valley, Calif	6
1918	Puerto Rico (killed by sea wave from earthquake in Mona Passage)	116
1925	Santa Barbara, Calif	13
1929	Grand Banks, New Foundland (killed by sea wave along Burin Peninsula)	Some
1933	Long Beach, Calif	120
1934	Kosmo, Utah	2
1935	Helena, Mont	4
1940	Imperial Valley, Calif	9
1946	Hawaiian Islands (killed by sea wave from earthquake in Aleutian Islands)	173
1949	Puget Sound	8
1952	Kern County, Calif	13
1954	Eureka-Arcata, Calif	1
1955	Oakland, Calif	1
1958	Khantaak Island and Lituya Bay, Alaska	5
1959	Hebgen Lake, Mont	28
1960	Hilo, Hawaiian Islands (killed by sea wave from earthquake off the coast of Chile)	61

Table 3.—*Damage caused by major United States earthquakes*

Year	Place	Damage [1]
1865	San Francisco, Calif	$500, 000
1868	San Francisco, Calif	750, 000
1872	Owens Valley, Calif	250, 000
1886	Charleston, S.C	23, 000, 000
1892	Vacaville, Calif	280, 000 to 600, 000
1898	Mare Island, Calif	1, 400, 000
1906	San Francisco, Calif	90, 000, 000
	Fire loss	1, 500, 000, 000
1915	Imperial Valley, Calif	2, 500, 000

[1] Based on 1950 evaluation of the dollar.

Table 3.—*Damage caused by major United States earthquakes*— Continued

Year	Place	Damage[1]
1918	Puerto Rico (damage from sea wave from earthquake in Mona Passage)	8, 000, 000
1925	Santa Barbara, Calif	8, 000, 000
1933	Long Beach, Calif	48, 000, 000
1935	Helena, Mont	4, 000, 000
1940	Imperial Valley, Calif	7, 200, 000
1941	Torrance-Gardena area, Calif	1, 200, 000
1944	Cornwall-Massena; Canada, New York	1, 800, 000
1946	Hawaiian Islands (damage from sea wave from earthquake in Aleutian Islands)	25, 000, 000
1949	Puget Sound, Wash	25, 000, 000
1949	Terminal Island (oil wells only)	9, 000, 000
1951	----do	3, 000, 000
1952	Kern County, Calif	60, 000, 000
1954	Eureka-Arcata, Calif	2, 100, 000
1955	Terminal Island (oil wells only)	3, 000, 000
1955	Oakland-Walnut Creek, Calif	1, 000, 000
1957	Hawaiian Islands (damage from sea wave from earthquake in the Aleutian Islands)	3, 000, 000
1957	San Francisco, Calif	1, 000, 000
1959	Hebgen Lake, Mont. (damage to timber and roads)	12, 000, 000
1960	Hilo, Hawaiian Islands and the west coast of the United States (damage from sea wave from earthquake off the coast of Chile)	25, 000, 000
1961	Terminal Island (oil wells only)	5, 000, 000

[1] Based on 1950 evaluation of the dollar.

SEISMOLOGICAL PUBLICATIONS OF THE COAST AND GEODETIC SURVEY

The following publications are available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

United States Earthquakes series, the annual seismological report of the Bureau. These are essentially statistical catalogs (available from 1945) of earthquakes felt over the entire country and outlying

territories. A summary of instrumentally determined earthquake locations is given in the later editions. Beginning with the 1933 report a section has been added on results of the strong-motion earthquake program of the Bureau. (Prices furnished on request.)

Earthquake History of the United States, Part I—Continental United States (Exclusive of California and Western Nevada) and Alaska, No. 41–1 (Revised (1956) Edition). This is a descriptive catalog of the stronger shocks of historical record through 1956.

Earthquake History of the United States, Part II—Stronger Earthquakes of California and Western Nevada, No. 41–1 (Revised (1960) Edition). This is a 55-page summary of the stronger earthquakes of the region. New data on many of the earlier shocks are included. Price 40 cents.

Earthquake Investigations in California, 1934–35, Special Publication 201. This is primarily of engineering interest and is rather technical as it concerns the precise measurement of ground and building motions resulting from natural and artificial causes, including earthquakes. A large quantity of observational data is given including data on normal and forced vibrations of buildings, elevated water tanks, bridges, and other structures; also data on ground vibrations. (Out of print.)

Principles Underlying the Interpretation of Seismograms, Special Publication 254. This is designed to meet the needs of the student and explain seismic waves and earth structure, the response of seismographs to seismic waves, travel-time tables and charts, interpretation of seismograms, and other items such as intensity, magnitude, and nomenclature.

Earthquake Investigation in the United States, Special Publication 282.

The following processed reports are available from the Director, Coast and Geodetic Survey, Washington 25, D. C.

The Seismograph and the Seismograph Station.—This is written primarily for use in the selection of seismographs and station sites for the recording of earthquakes. It briefly treats on factors governing site selection; choice of instruments, including seismometers, galvanometers, and recorders; time control; telemetering seismic signals; amateur seismology. Price $0.30.

Seismological Bulletin.—This pamphlet contains the seismogram interpretations for all Coast and Geodetic Survey and cooperating stations and gives resulting epicenter locations. Issued monthly on mailing list CGS–7.

Preliminary Determination of Epicenter Cards.—These postal cards give epicenter locations of strong shocks occurring throughout the world, and are issued twice weekly and within two weeks after occurrence of shocks.

Abstracts of Earthquake Reports for the Pacific Coast and the Western Mountain Region.—These quarterly reports contain the unabridged

information that has been collected from thousands of volunteers and other observers who furnish information on felt earthquakes. Issued on mailing list CGS–3.

Quarterly Engineering Seismology Bulletin.—This leaflet contains brief summaries of work connected with the engineering phase of seismology and preliminary analyses of all accelerograph records obtained during the period. Issued on mailing list CGS–5.

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